Aeroelastic studies at National Aerospace Laboratory: a review

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Aeroelastic instabilities encountered often by lifting surfaces of a flight vehicle lead to catastrophic failures. Hence, the objective of the designer is to make sure that such a phenomenon does not occur within the flight envelope. In this paper, both theoretical and experimental aeroelastic studies on aircraft and space vehicles carried out at NAL during the last three decades are reviewed briefly.

Introduction

In order to achieve good performance and high manoeuverability, modern aircrafts and space vehicles are designed to have light weight, which in turn makes the vehicles highly flexible. But unfortunately, these flexibilities may lead to aeroelastic instabilities during its flight region. These instabilities may adversely affect the performance characteristics of the vehicle and/or may sometimes cause failures. These unwanted aeroelastic phenomena occur due to interaction of elastic, inertial and steady/unsteady aerodynamic forces induced by the structural deformations. Aeroelastic instabilities within the operating envelope have to be avoided to meet the main requirement in aerospace vehicle design. The various aeroelastic problems that have to be addressed in the design stage itself are shown in Figure 1.

There are two methods of ascertaining the aeroelastic behaviour of aero structures, one is by calculation and the other by experiment. There is nothing to prevent both methods from being adopted for solving the same problem, so that the results obtained from one method become a valuable check on the other.

In this paper, both theoretical and experimental studies on aircraft and space vehicles carried out at NAL during the last three decades are reviewed briefly.

Aeroelastic studies

Analytical work

A number of analytical procedures for dynamic and aeroelastic analysis have been evolved using discrete approaches or continuum approaches. At present, numerical

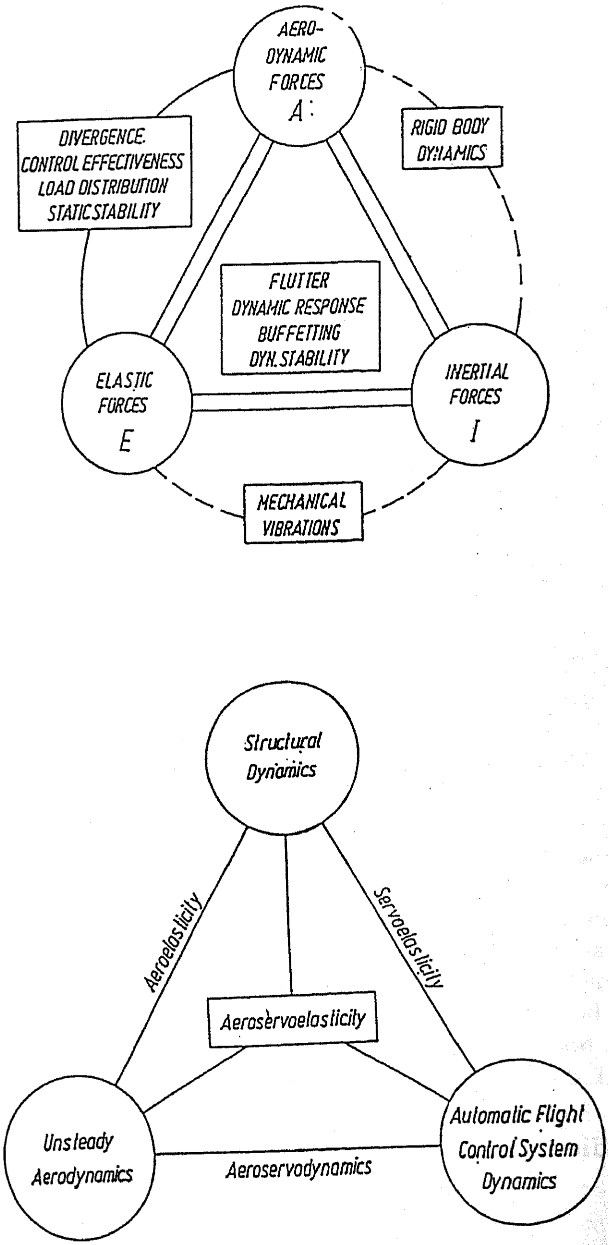

Figure 1. (**a**), The aeroelastic triangle of forces; (**b**), aeroservoelastic interaction

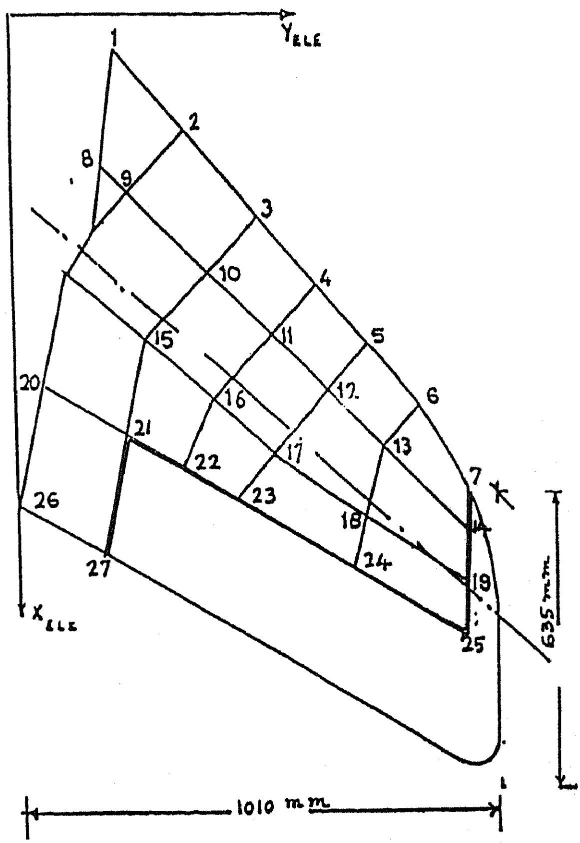

Figure 2. Experimental a/c horizontal stabilizer along with structural grids.

calculation method, commonly known as finite element method (FEM), enables accurate determination of natural frequencies, mode shapes and generalized masses.

Having a knowledge of the characteristics of mode shapes and natural frequencies of the flight vehicle, the unsteady/steady air loads could be estimated using the doublet lattice method, Mach box, piston theory or vortex lattice method depending upon the flow regime and the type of aeroelastic problem. Consistent efforts have been made at NAL over the years to develop softwares for these methods. During the year 1982, horizontal stabilizer of Ajeet Aircraft was analysed for flutter characteristics using the software developed at NAL. Figure 2 shows the stabilizer while Figure 3 gives its flutter characteristics. Another problem studied using NAL-developed software was aeroelastic tailoring of unswept and forward-swept advanced composite wings for divergence constraints. This was because general-purpose programs like NASTRAN, then available,

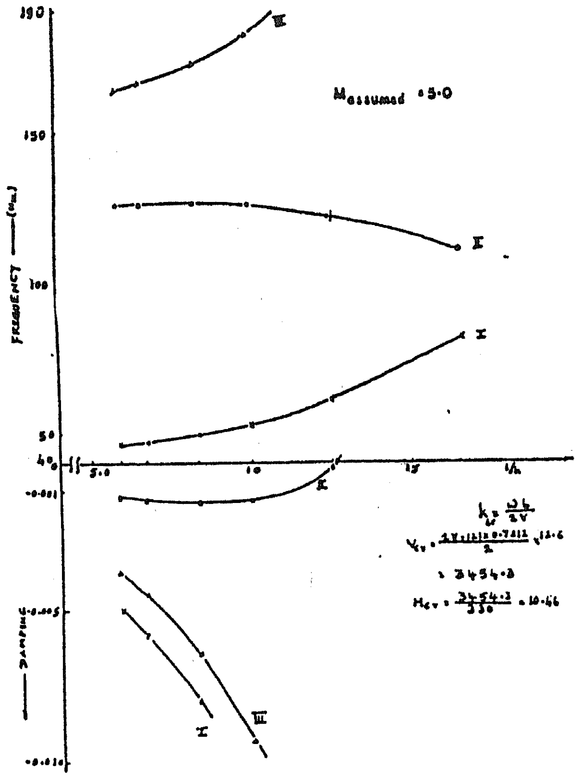

Figure 3. Experimental a/c horizontal stabilizer–flutter curve – supersonic regime.

were not supporting static aeroelastic studies. Figure 4 shows the divergence elimination by aeroelastic tailoring.

Since 1986, NASTRAN has been used for dynamic and aeroelastic stability analysis of aircraft structures like LCRA wing, wing and empennage of HANSA and typical missile wing configurations. Figure 5 shows the FE model of HANSA wing configuration and Figure 6 shows the flutter characteristics of the wing. Continuously, work is progressing in NAL on improving the modelling and prediction of theoretical aeroelastic characteristics.

Experimental studies

It is often difficult and at times impossible to model the complex aircraft structure mathematically to predict accurately the static/dynamic behaviour of the structure. Hence,

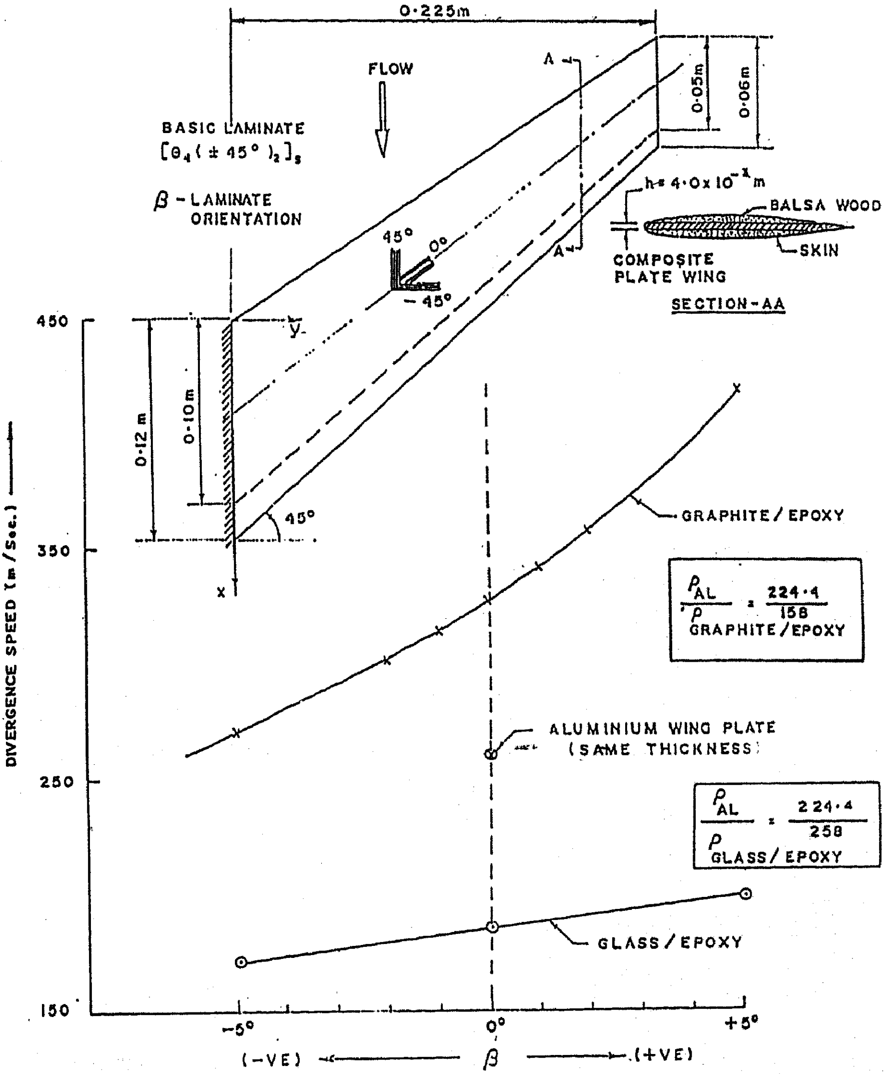

Figure 4. Divergence elimination by aeroelastic tailoring.

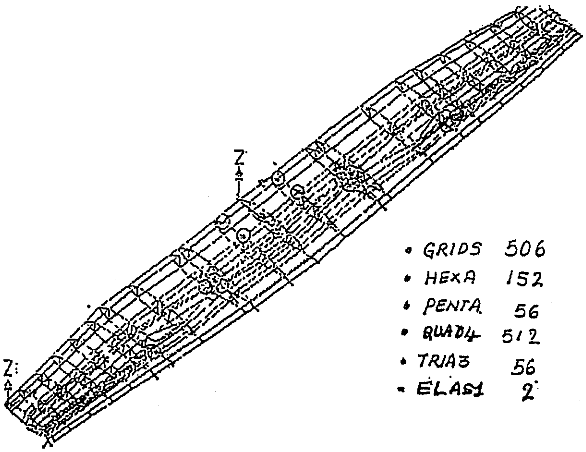

Figure 5. NAL LA-2C wing dynamic model.

the designer has to check by experimental means, involving model design, model construction, ground testing, wind tunnel testing and data interpretation by judicial means on scaled aeroelastic models. With these aims in mind, structures carried out at NAL during the last three decades. The following sections review briefly studies on aerospace.

Types of instabilities investigated

The works undertaken may be broadly classified as aircraft models and space launch vehicle structures. Normally, lifting surfaces like aircraft wings may experience dynamic instability like flutter, whereas launch vehicle structure may experience divergence and buffet-type failure during the flight region.

HJT-16 wing model (1968)

As early as 1965, a 1/10th-scale low-speed–high aspect ratio flutter wing model of Hindustan Jet Trainer aircraft wing was designed, fabricated and tested in wind tunnel. In this model, the elastic properties are simulated by a single perspex spar having variable rectangular cross section placed at the elastic axis. The aerodynamic shape is generated by ten balsa segments placed along the spar and the inertial properties are simulated using lead weights. The model was tested in 9' × 5' elliptical cross section closed-circuit wind tunnel at IISc. Figures 7 and 8 show the model and the static test of the model.

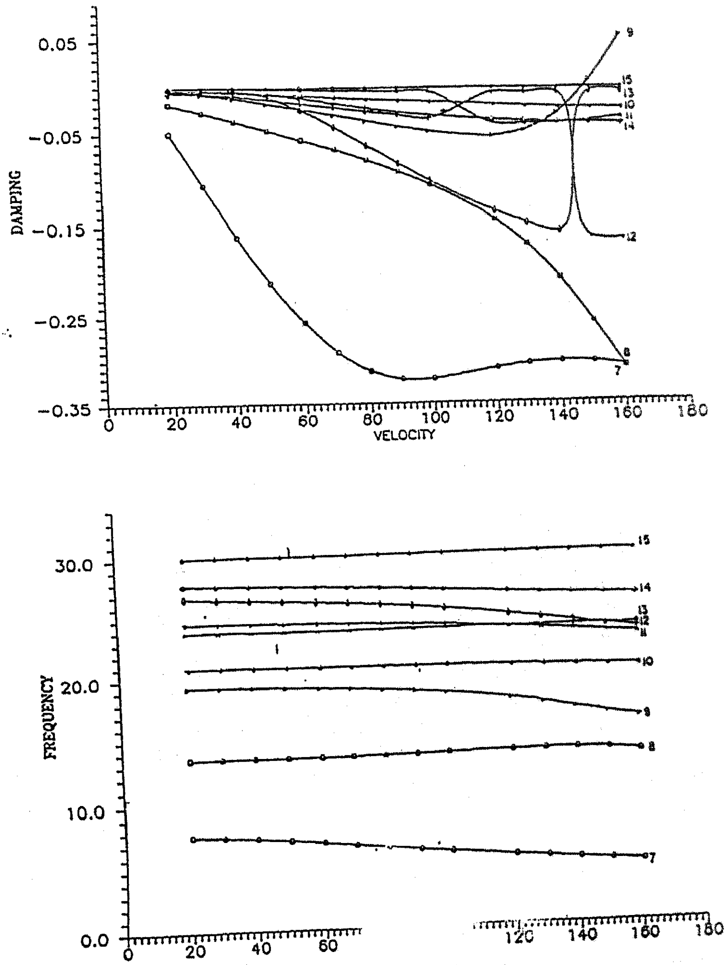

Figure 6. NAL LA–2C flutter curve.

HF-24 wing flutter model (1973)

A 1/10th-scale replica-type of construction having spars, ribs and thin aluminium skin covering has been worked out. Exhaustive static and dynamic tests were carried out and then the model was tested at NAL 4' × 4' trisonic wind tunnel. at a supersonic Mach number. Figure 9 shows the construction details of the model, dynamic test setup and the model along with protection device mounted in the wind tunnel.

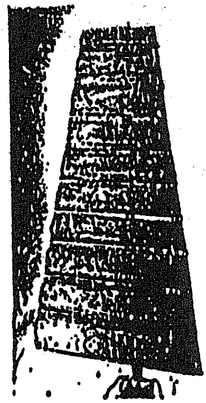

Figure 7. HJT-16 1/10-scale flutter model.

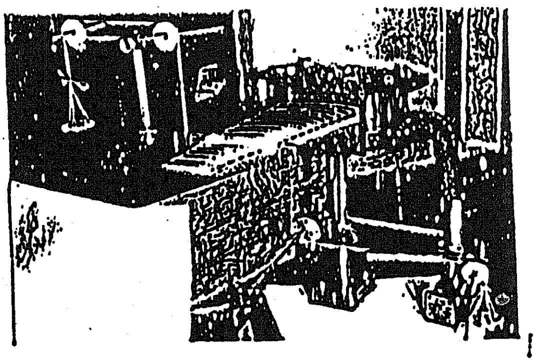

Figure 8. HJT-16 wing flutter model under static test.

Divergence studies of launch vehicles

Launch vehicles having a slenderness ratio (L/D) more than 20, are prone to divergence instabilities. Divergence is a static aeroelastic phenomenon which occurs due to interaction between elastic and aerodynamic forces. With this in mind, a programme to investigate the body divergence characteristics of SLV-3 was undertaken. Aeroelastic models of 1/45th, 1/20th and 1/15th-scale were designed, fabricated, ground-tested and wind-tunnel-tested at Mach numbers 2, 2.5 and 3.3 at an angle of attack of 1°. Stiffness as simulated by spar and aerodynamic shape is given with balsa wood. Figure 10 shows the spars for the models and the completed model. Figure 11 shows the model mounted on the sting in the 4' × 4' wind tunnel and 1' × 1' wind tunnel.

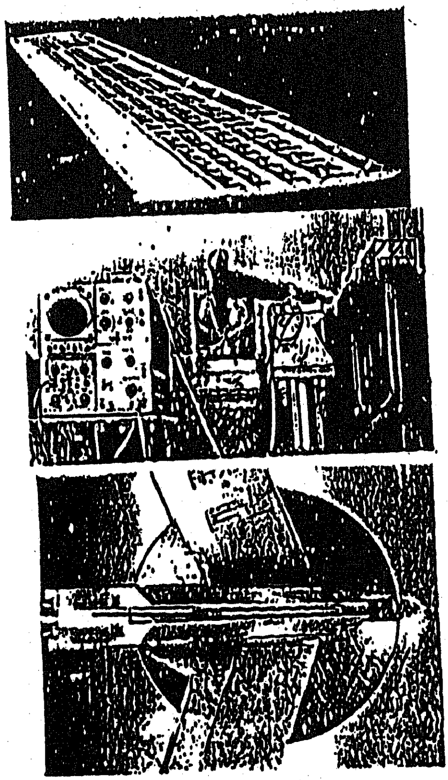

Figure 9. HF-24 wing flutter model test sequences.

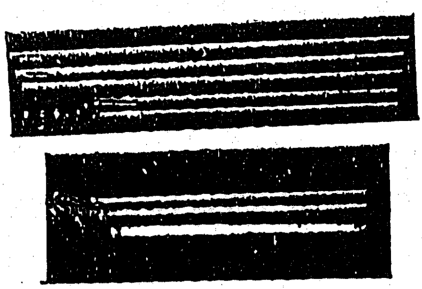

Figure 10. Spars for SLV-3 divergence model for different scales and constructed model.

Figure 11. SLV-3 divergence models mounted in NAL supersonic tunnel.

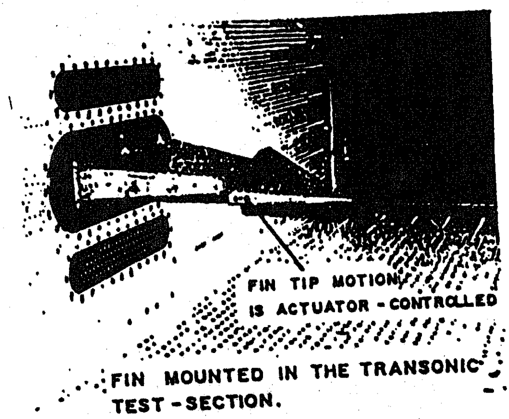

Figure 12. Servoelastic SLV-3 fin proto model in NAL wind tunnel.

Aeroservoelastic tests on a fin proto at transonic flow (1980)

An experimental study was undertaken to establish the flutter behaviour and performance characteristics of a launch vehicle fin in transonic flight regime. At transonic speeds, a complex interaction between the moving shock wave and the boundary layer takes place resulting in random unsteady aerodynamic loads. Structural instability can result from an

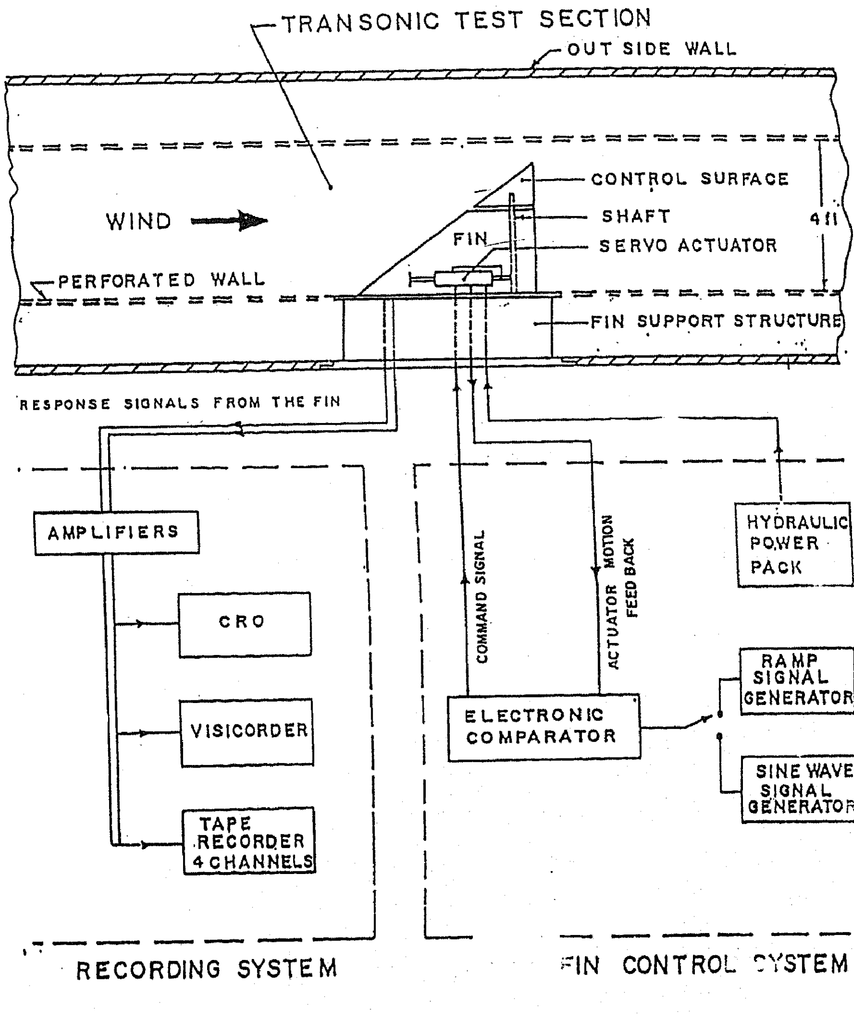

Figure 13. Layout for transonic flutter testing.

adverse coupling between aerodynamic, servocontrol elastic and inertial forces. Figure 12 shows the model mounted in the wind tunnel test section. The proto vehicle has a fin tip which is moved with an actuator system. The tests were conducted for different fin tip controls as shown in Figure 13. A typical result is shown in Figure 14. The test results proved the qualification of the structure from flutter point of view.

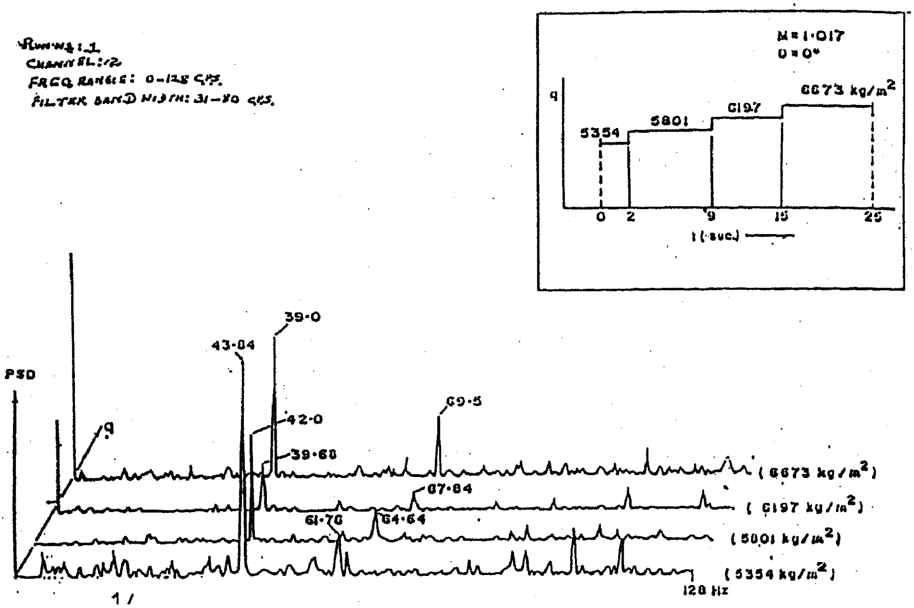

Figure 14. A typical result for transonic flutter test.

Table 1a.

Model	Method	Mode no.	Frequency (Hz)	Damping	Remarks
Cantilever plate model	Free decay	1	30.99	0.01527	Impulse excitation
	Free decay with oscltr cut off	1 2	31.7 106.0	0.02215 0.01328	Sinusoidal excitation
	Amplitude plot	1 2	31.2 103.22	0.0224 0.01448	Sinusoidal excitation
	PSD plot (digital)	1 2	32.33 103.22		White noise excitation
	ACF (digital)	1 2	 102.4	 0.01545	White noise excitation
	RDM (digital)	1 2	31.9 103.11	0.018424 0.013012	White noise excitation

Table 1b.

Wind tunnel model	Run no. Angle of attack	Method	Mode no.	Frequency (Hz)	Damping	Remarks
ASLV (1/20)	10564 0°	ACF	1	64.10	0.021945	Excitation by tunnel turbulence
ASLV (1/20)	10564 0°	RDM	1	64.0	0.022815	
ASLV (1/20)	10564 0°	PSD (digital)	1	35.37	–	Model pitching
ASLV (1/20)	10564 0°	PSD (digital)	2	68.77	–	First free-free
ASLV (1/20)	10564 0°	PSD (digital)	3	120.75	–	
ASLV (1/20)	10564 0°	PSD (digital)	4	166.49	–	Second free-free
ASLV (1/20)	10564 0°	PSD (digital)	5	241.70	–	Coupled mode

Buffet response for ASLV (1983)

Transonic buffeting of a launch vehicle is a phenomenon where the vehicle is subjected to severe fluctuating pressures caused by separated flows and shock boundary oscillations during the transonic phase of its trajectory. It is a serious problem that needs careful study since it may lead to failure of the vehicle. Buffet pressures are found to be significant in launch vehicles with bulbous nose configurations. Hence, it was aimed to study the transonic buffet response of ASLV through aeroelastic modelling and testing. Figure 15 shows the sequence of fabrication details. Figure 16 shows the completed model. Figure 17 shows ASLV buffet model mounted in 4' × 4' trisonic wind tunnel test section and one typical test result is presented in Figure 18.

Transonic buffet response of PSLV (1988)

PSLV, which has been designed to carry a pay load of 1000 kg, also has a bulbous nose portion and six straps on boosters. A 1/40th-scale aeroelastic model was designed and fabricated to match the characteristics of NAL trisonic tunnel. Figure 19 shows the model construction details. This model was tested at NAL at transonic Mach number after detailed static/dynamic ground tests. Figure 20 shows the model mounted in the wind tunnel.

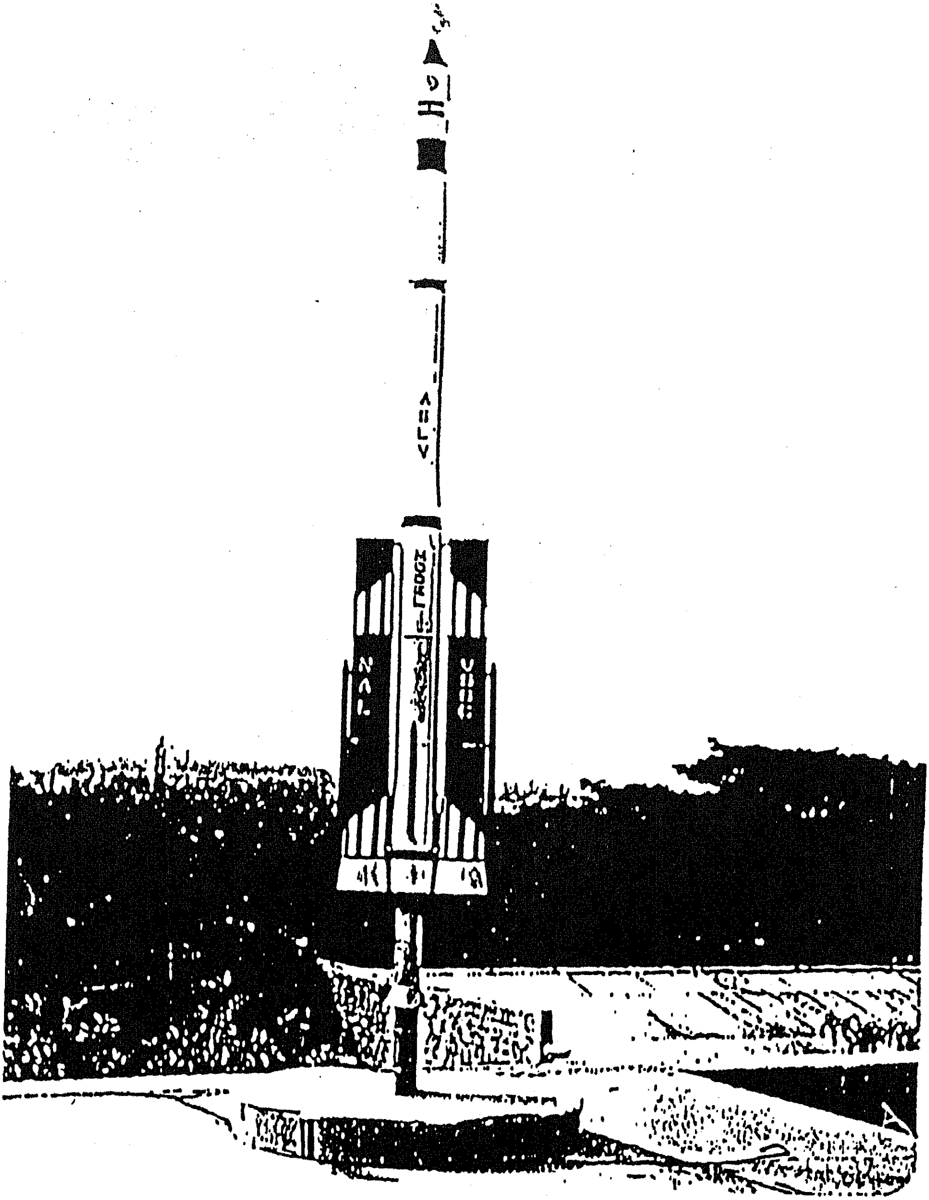

Figure 16. Completed ASLV buffet model.

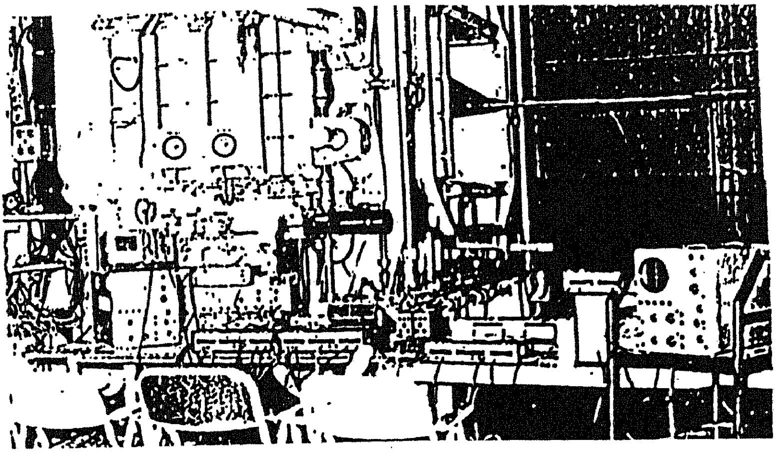

Figure 17. ASLV buffet model mounted in 4' × 4' trisonic wind tunnel, NAL.

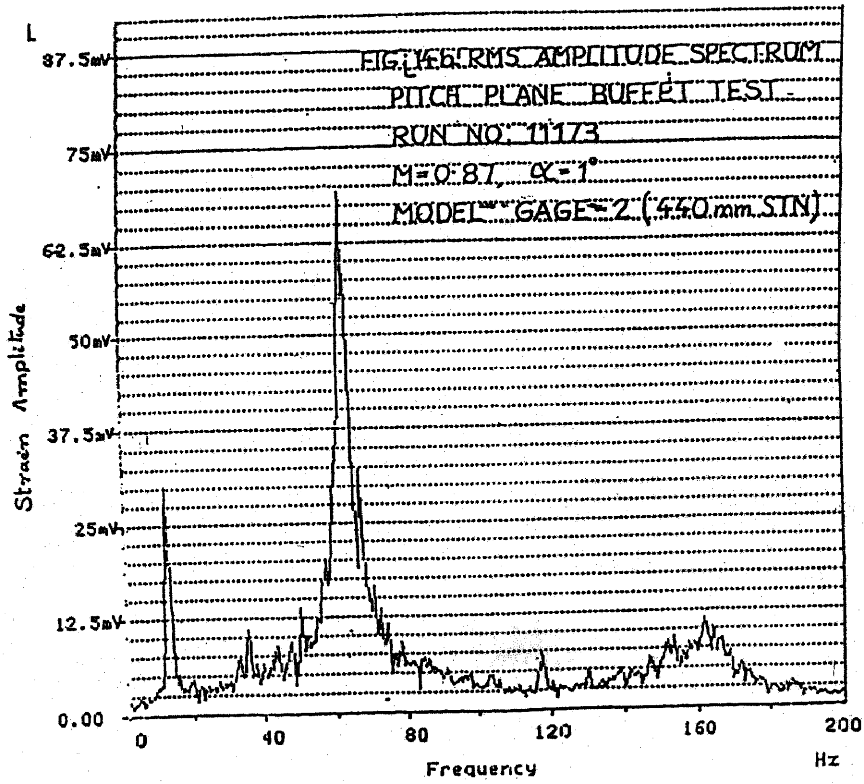

Figure 18. One typical test result obtained for buffet response

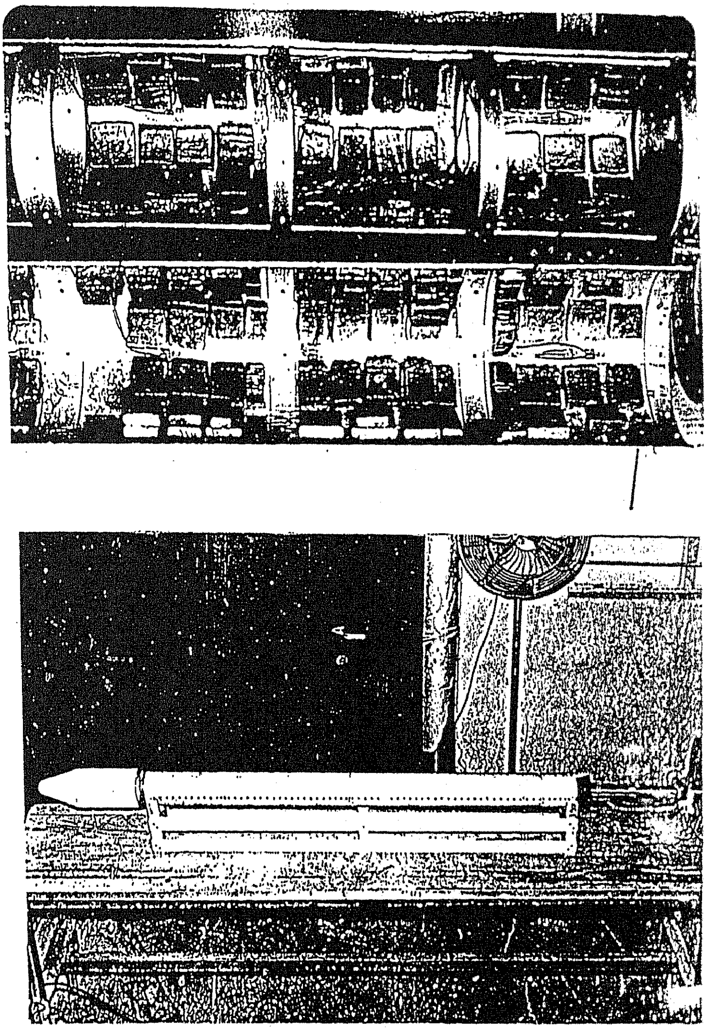

Figure 19. Construction details for PSLV model for buffet studies.

Data analysis

Wind tunnel tests are carried out on the designed elastic wing models with the aim to extract the aeroelastic characteristics of the vehicle for different flight conditions. That is

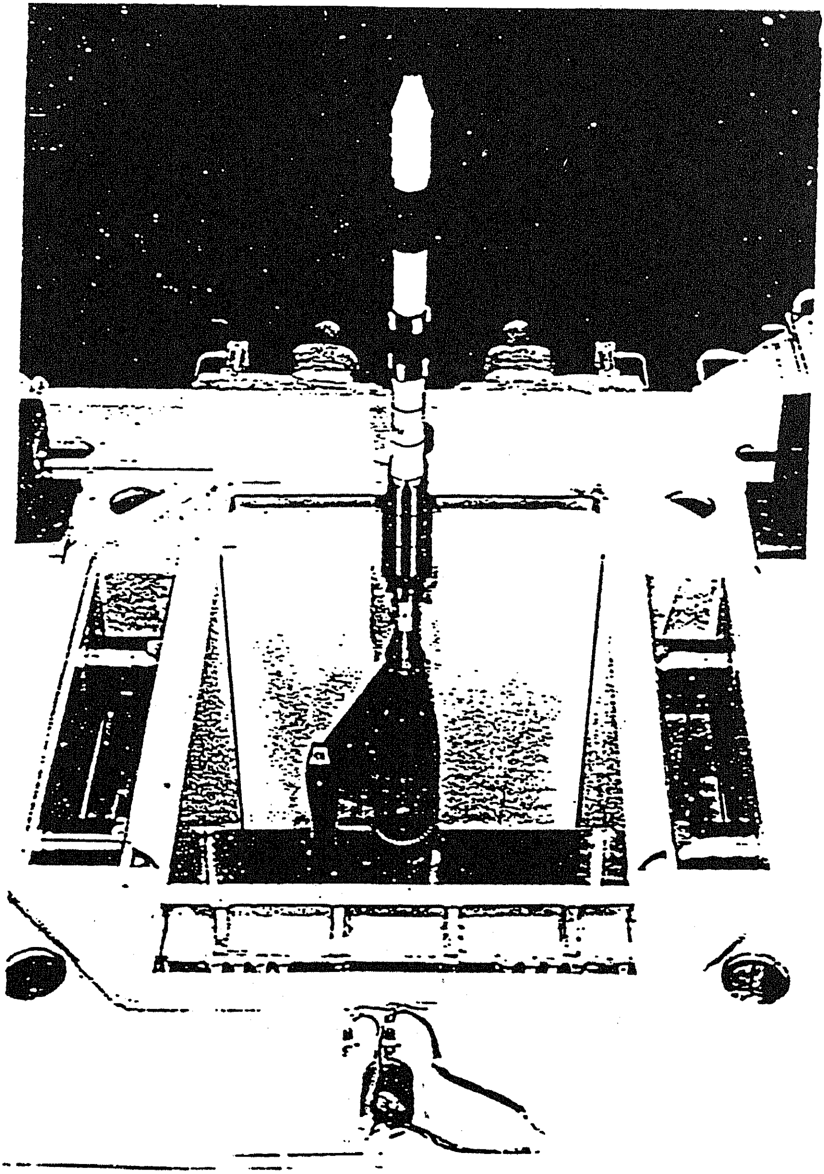

Figure 20. PSLV model mounted in NAL wind tunnel.

to say, how the modal characteristics like natural frequencies and modal damping of the lifting surfaces under external unsteady air loads are changing with change in flight speed.

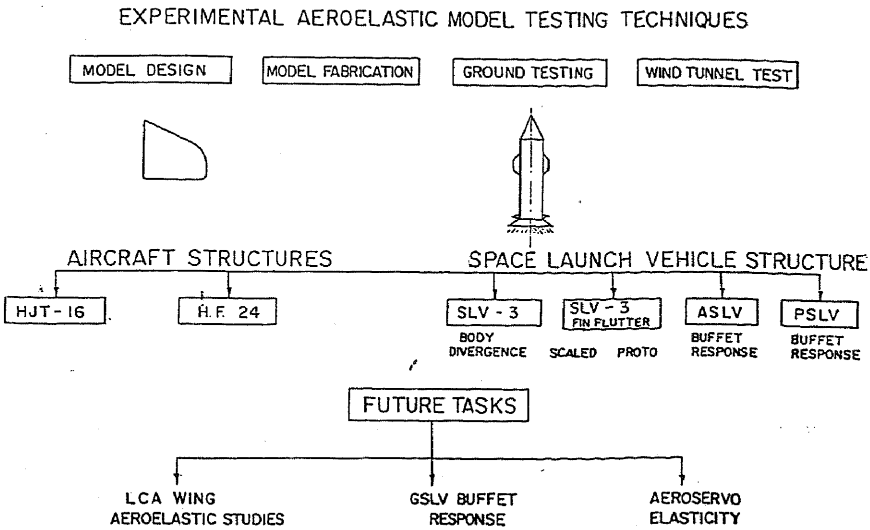

Figure 21. Chart showing the works accomplished at NAL.

For this purpose a software was developed at NAL to estimate the power spectral density and autocorrelation function and do the random decrement analysis to predict the natural frequencies and damping coefficient in each mode. Here it is assumed that the exciting unsteady aerodynamic force has constant PSD. Table 1 shows the results obtained using the NAL software. Further, NAL has signal analysers which can perform a number of functions.

Wind tunnel tests on PSLV, ASLV, etc., are carried out with the aim to obtain buffet loads that give additional strains on the structure. At NAL an extensive procedure has been developed to obtain buffet load.

Conclusion

Figure 21 shows the tasks accomplished by aeroelasticity group of the Structures Division. We can conclude that NAL is a premier institution which has gained a rich experience and has developed a vast expertise in the field of dynamics and aeroelasticity to undertake any challenging, important national tasks in this crucial area.

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